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Origin of Mesoproterozoic A-type granites in Laurentia: Hf isotope evidence

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Abstract

Granitic rocks are commonly used as a means to study chemical evolution of continental crust. In particular, their isotopic compositions reflect the relative contributions of mantle and crustal sources in their genesis. In Laurentia, a distinctive belt of Mesoproterozoic A-type or "anorogenic" granites of ∼1.4 Ga age was emplaced within composite, heterogeneous Proterozoic crust. Zircons are an ideal mineral to constrain the granite petrogenetic history because they are repositories of both age (U–Pb geochronology) and tracer (Lu–Hf isotopic) information. We measured the Hf isotope composition of zircons from 31 previously dated A-type granites intruding Proterozoic basement provinces from the southwest U.S. to the upper mid-continent. Isotopic compositions for all granites are broadly similar, with average $^{176}Hf/^{177}Hf(i)$ ratios of 0.281871–0.282153. Averages for granites within different crustal provinces yield present-day ε_{Hf} values between −31.9 and −21.9. Initial ε_{Hf} values discriminate the granites by age of the 2.0–1.6 Ga crust which they intrude, but are independent of intrusion age, as follows (basement formation ages in parentheses): southern Granite–Rhyolite (1.5–1.3 Ga), +7.0±0.9; central Yavapai (1.8–1.7 Ga), +5.4±0.9; western Yavapai (1.8–1.7 Ga), +3.3± 1.1; Granite–Rhyolite (1.5–1.3 Ga), +1.4±0.6; Mojave (1.8–1.7 Ga), +0.2±0.8; and Penokean (1.9–1.8 Ga), −0.1±n/d. The narrow ranges of Hf isotopic signatures within these regional groupings of granites reflect the age and isotopic composition of the basement provinces they intrude. Granites in the southern Granite–Rhyolite and central Yavapai provinces have the highest initial ε_{Hf}, reflecting their more juvenile sources, whereas Mojave and Penokean granites show contributions from more evolved crustal sources. Simple calculations indicate that all the granites represent dominantly crustal melts; although a mantle contribution cannot be ruled out, if present it must be minor. The Hf isotope compositions of the 1.4 Ga granites appear controlled predominantly by widespread melting of heterogeneous 2.0–1.6 Ga lower crust, consistent with other geochemical indicators. In addition to constraining granite petrogenesis, the distinct age and Hf isotope signature of the zircons will prove useful as a provenance tracer in detrital zircon suites from Neoproterozoic and younger siliciclastic deposits worldwide.

Keywords: Mesoproterozoic; Hf isotopes; granite petrogenesis; Laurentia; crustal evolution

1. Introduction

Granitic rocks are commonly used as a means to study chemical evolution of continental crust. In particular, their isotopic compositions reflect the relative

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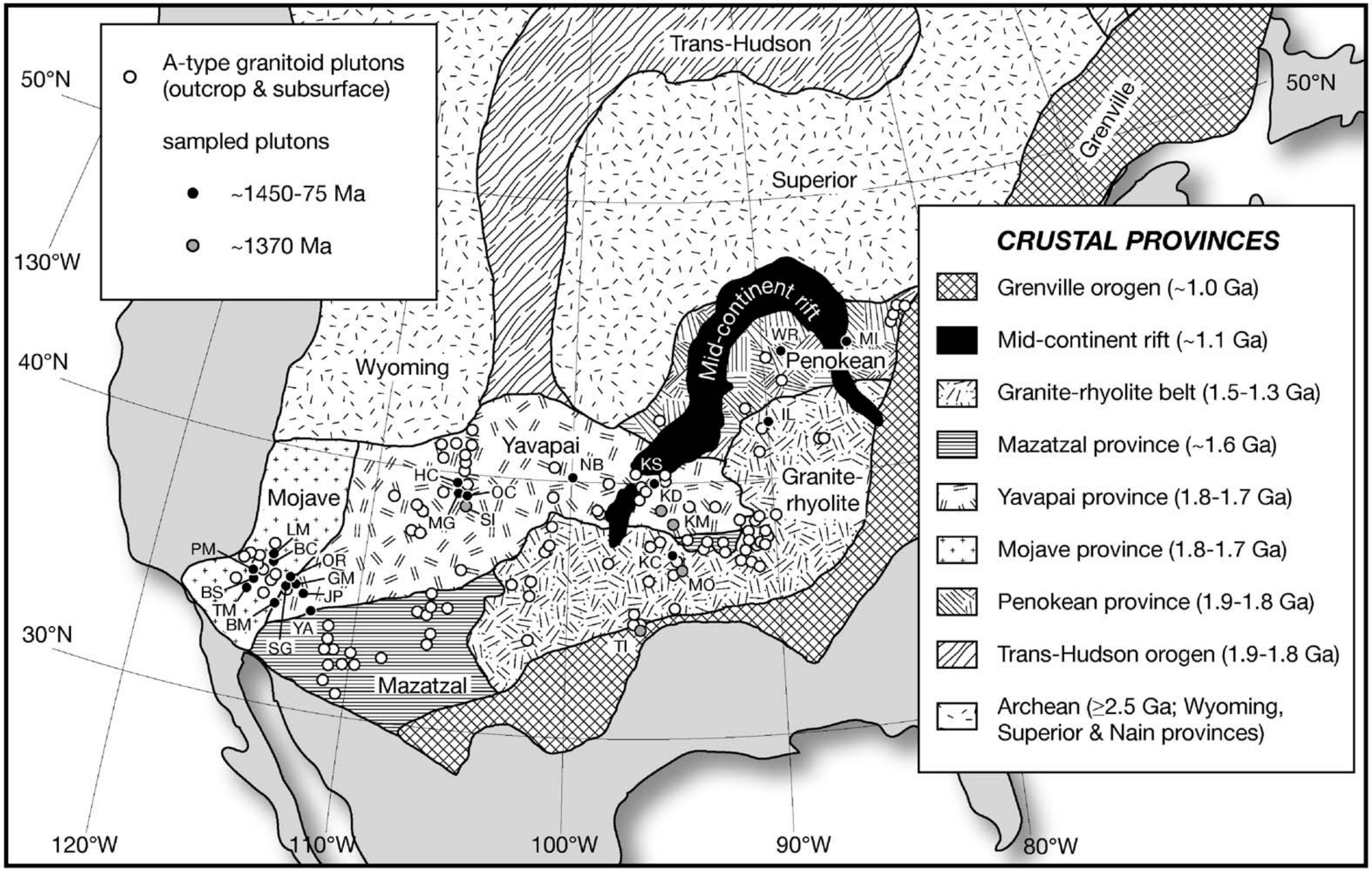

Fig. 1. Map of southern North America showing major Precambrian crustal provinces (after [1,6,20]) and locations of dated Mesoproterozoic granitoids (white circles). Mesoproterozoic granites are known from outcrop and, particularly in the mid-continent region, subsurface drilling. Sampled granites of this study generally fall into two ages modes (Fig. 2) at ~1370 Ma (gray circles) and ~1450–1475 Ma (black circles).

contributions of mantle and crustal sources in their genesis and can be used to constrain their tectonic setting of formation. Because granitic rocks have formed in a variety of tectonic settings over most of Earth history, they hold important information about the evolution of continental crust. In Laurentia, a distinctive belt of Mesoproterozoic A-type granites of ~1.4 Ga age was emplaced across an assembly of composite Paleoproterozoic and Mesoproterozoic crust extending from California to Wisconsin (Fig. 1; [1–6]). In contrast to granites formed in subduction-zone settings, A-type granites are typically high in SiO_2, have markedly low LIL/HFS-element ratios suggestive of cratonic and/or rift-zone settings, and they are commonly associated with crustal extension features. A-type granites appear to represent significant (up to 20% in some provinces) magmatic crustal additions worldwide, particularly between ~1.8 and 1.0 Ga [7]. Originally, the Laurentian A-type granites were so named because it was believed they had an "anorogenic" origin, unrelated to an orogenic (i.e., convergent or collisional) tectonic setting. In this view, the Laurentian A-type granites were thought by many workers [1,8] to represent a globally important episode of crustal heating and anorogenic magmatism, although this interpretation has been questioned by studies showing evidence of syn-tectonic granite emplacement [9–12]. Previous Nd- and Pb-isotope data from these and other intrusions were used to establish a broad framework of crustal development in southwestern Laurentia [13–15]. These studies provided important constraints on granite petrogenesis, the age distribution of Laurentian crustal provinces, and the growth of continental crust in the western U.S. In detail, these and other studies have demonstrated a period of rapid Paleoproterozoic (1780–1650 Ma) crustal growth followed by accretion to an Archean nucleus and remobilization during crustal melting [16–18].

Age and isotopic studies using zircon are a useful complement to whole-rock isotopic data in interpreting the petrogenetic history of granitic rocks. Zircons are not only the principal mineral for determining the most precise crystallization ages using the U–Pb isotopic system but they are also highly enriched in Hf (generally about 10,000 ppm or 1%). These features, combined with their low Lu/Hf ratios and their resistance to isotopic disturbance, make zircons ideal repositories of both age (U–Pb geochronology) and tracer (Lu–Hf isotopic) information. In this study, we measured the Hf isotope compositions of zircons from a geographically diverse suite of well-dated A-type Laurentian granites that intrude Proterozoic basement provinces from the southwest U.S. to the upper mid-continent (Fig. 1). These granitoid intrusions were emplaced within a variety of crustal age provinces, such that their isotopic compositions should provide information about the relative proportions of crust and mantle contributions in their genesis. The new data can help to evaluate various models for origin of the granites, including those invoking "anorogenic", syn-orogenic/accretionary, and post-orogenic processes.

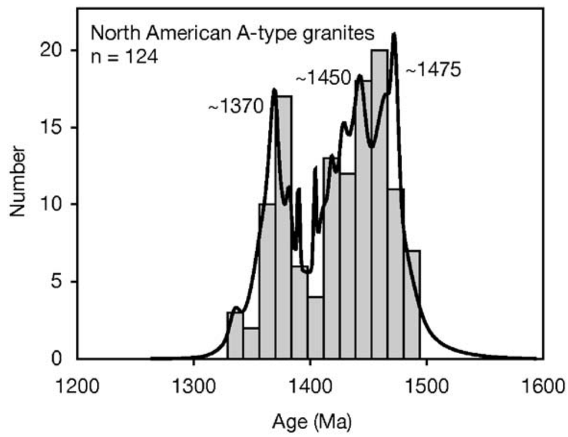

Fig. 2. Histogram and relative probability distribution of 124 dated granitoid plutons in North America, showing major modes of ~1370 and 1450–1475 Ma. All ages from conventional U–Pb zircon data, compiled from [1,6,59,60,74–76].

In addition to information about igneous petrogenesis and the origin of the A-type granite province itself, the new Hf isotope data may also prove useful as a provenance tool. Distinctive igneous and metamorphic crustal provinces such as the Neoproterozoic Grenville orogen (Fig. 1) are known to produce detrital zircons that became sequestered in large populations within younger sedimentary deposits [19]. Because the Mesoproterozoic Laurentian granites comprise a similarly extensive igneous belt of unique age globally, sedimentary dispersal of zircon from these granites has the potential to serve as a distinctive fingerprint of sedimentary provenance in Neoproterozoic and younger siliciclastic deposits.

In this paper, we review briefly the pertinent characteristics of the Laurentian A-type granite belt related to their origin and present new Hf isotope data obtained from zircon in order to document isotopic variability within the belt and evaluate models proposed for their origin. We also show that the unique age and isotopic signatures of the Laurentian granites may have significant use as a provenance tracer in paleogeographic models of Rodinia because of their presumed central location in the Neoproterozoic supercontinent.

2. Nature of Mesoproterozoic A-type magmatism in Laurentia

Mesoproterozoic A-type granitoids can be traced from the southwest U.S. to the central mid-continent of North America, and they are correlated in age with anorthositic bodies farther to the northeast in Canada (Fig. 1; see [1,6,20]). Collectively, gabbros, anorthosites, charnockites, intermediate mangerites, and granites (so-called ACMG suite) of this age in Laurentia represent one of the largest consanguineous continental magmatic provinces on Earth and are thought to correlate generally with somewhat older plutonic rocks intruding the Baltic shield [21,22]. The granitic intrusives crystallized from alkali-rich magmas and typically have distinctive coarse-grained rapakivi textures. They are commonly called "anorogenic" granites [1], but because the genetic implications of this term are disputed, we refer to them here geochemically as A-type granites [23–25]. U–Pb zircon ages show that the Laurentian granites fall into two broad age ranges with major modes at ~1370 and ~1450–1475 Ma (Fig. 2).

Detailed study of Laurentian A-type granites over more than two decades provides a sound petrologic foundation for our isotopic study. The A-type granites in this magmatic belt share the following general characteristics [1,3,5,26]: (a) they have alkaline to peralkaline, intracratonic or "within-plate" trace-element compositions; (b) most are metaluminous, but some are peraluminous; (c) they typically have high-K, high-LIL, high-REE, and high-Fe/Mg compositions; (d) they have $f(O_2)$ and $f(H_2O)$ indicating variable redox conditions but generally dry magmas; (e) the granites crystallized from deep-seated magmas with high liquidus temperatures (900–1300 °C) and high crystallization temperatures (up to 800 °C); and (f) most are ≥200 Ma younger than their host crustal province and intrude crustal provinces with juvenile (i.e., mantle-derived) geochemical and isotopic characteristics.

Mineralogical and O-isotope relations show that the granitoids may be divided into distinct ilmenite-bearing, magnetite-bearing, and two-mica groups [1,3–5,26] that may reflect variations in lower-crustal source regions across Laurentia. For example, low-$f(O_2)$, ilmenite-series units such as the Sherman batholith in Wyoming [5,27,28] may reflect partial melting of a reduced lower-crustal source related to emplacement of the Laramie anorthosite, whereas the high-$f(O_2)$ magnetite-series rocks, more typical of the Laurentian A-type magmatic province, require a more oxidized and chemically evolved source. The peraluminous, two-mica types probably require significant proportions of melting of a metasedimentary source.

Petrologic data indicate that the Laurentian A-type granitoids formed by low degrees of partial melting under generally dry, high-temperature conditions [3,5]. Suggested models for the origin of these alkaline–granite melts fall into three major categories: (1) crustal melting by active mantle heating in a so-called "anorogenic" setting [2,3,5,21,22,29–35]; (2) syn-orogenic magmagenesis related to accretionary crustal deformation and metamorphism, perhaps in a transpressional regime [9–12]; and (3) melting of previously thickened and thermally insulated warm crust during a post-orogenic phase of Proterozoic lithospheric growth and supercontinent amalgamation [4,8,36]. Anderson and Morrison [4] provide a comprehensive review of these models. In general, the "anorogenic" models require an advective mantle heat source, which may include active crustal extension and rifting coupled with rising mantle asthenosphere, mantle upwelling or diapirism (perhaps related to plume activity), mafic underplating, lithospheric delamination, or some combination of these. The arguments in favor of an active, orogenic setting for these magmas focus on the occurrence of foliation and fabric development in many plutons, and regional low-grade (300–350 °C) metamorphism that caused widespread resetting and/or closure of mica Ar cooling ages [9–12,37].

For our purposes in this paper, key features of the Laurentian A-type granitoids that must be explained by any petrogenetic model include: (1) low degree of partial melting (10–30%; [1]), but a high fraction of juvenile crustal source material; (2) Nd-, Sr- and O-isotope compositions that indicate derivation from 1.9 to 1.7 Ga crust with little evidence of Archean source components [3,13,14]; (3) the most primitive compositions in the association are fundamentally granitic and show no evidence for fractionation from more mafic magmas [26]; (4) there is no definitive evidence for calc–alkaline magmatic-arc signatures related to a subduction-zone magmatic process; (5) the granitoids were emplaced into Paleoproterozoic terranes that are typically 200–300 Ma older; and (6) the A-type magmatism represents a continental-scale event following major crustal construction, yielding a vast and

Table 1
Summary of Mesoproterozoic granites used in this study

Area	Granite ages (Ga)	Sample no.	Rock unit, location	Map reference	Age province [a]	U–Pb age (Ma)	±	Reference [b]	Collector [c]
Mid-continent	1.43–1.47	IACK-001	Kansas Univ., #1 Peterson (granite)	KC	GR	1433	6	[6]	WRVS
		ILST-003	Commonwealth Edison UPH-3 (granite)	IL	GR	1465	8	[6,80]	
		KSMS-044	Houston Int. Min. Vermilion (granite)	KS	Y	1428	3	[6]	
		NBFN-001	Tenneco Oil, #1 LeMaster (granite)	NB	Y	1436	8	[6]	
		MI 81–12	Shell Oil, State Blair 2–24 (granite)	MI	P	1472	2	[13,80]	
		VS70-91a	Wolf River granite	WR	P	1475	2	[78]	
Mid-continent	1.34–1.37	KSDG-3	USGS/KGS, Hydro test (granite)	KD	GR	1339	12	[6,75,76]	MBE
		TISH	Tishomingo granite	TI	sGR	1374	15	[6,75,76]	
		KSMI 4	USGS/KGS, Hydro test (granite)	KM	GR	1361	6	[6,75,76]	
		MOMC2	AMAX, HC-1 (granite)	MO	sGR	1367	3	[6,75,76]	
Colorado	1.37–1.47	SC-2	San Isabel monzogranite	SI	Y	1362	7	[74]	MBE
		SD-2	San Isabel monzogranite	SI	Y	1377	14	[74]	
		RV-1C	Oak Creek monzogranite	OC	Y	1442	7	[74]	
		CO-7	West McCoy Gulch monzogranite	MG	Y	1474	7	[74]	
		CO-9	West McCoy Gulch monzogranite	MG	Y	1460	21	[74]	
		NOB-1	sill in Hardscrabble Creek	HC	Y	1441	82	[74]	
NW Arizona	1.39–1.40	KCAZ98-10	Long Mountain	LM	Mo	1390	1	Unpublished	KRC
		BW-1	Boriana Canyon	BC	Mo	1404	2	[79]	
West-central Arizona	1.40–1.42	JW-10	Mafic granodiorite	AD	Mo–Y	1410	4	[59]	JLW
		JW-13	Granite of Olea Ranch	OR	Mo–Y	1418	2	[59]	
		JW-15	Granite of Olea Ranch	OR	Mo–Y	1418	2	[59]	
		1164	Signal granite	SG	Mo–Y	1410	4	[59]	
		1168	Signal granite	SG	Mo–Y	1410	4	[59]	
		A-151a	Granite of Joshua Tree Parkway	JP	Y	1414	5	[59]	
		A-153	Granite of Grayback Mountain	GM	Y	1414	5	[59]	
		B565	Buckskin Mountains granite	BM	Mo–Y	~1400	–	[59]	
		JW-122	Yarnell granodiorite	YA	Y–Ma	~1421	–	[59]	
Eastern California	1.40–1.43	JW-4	Turtle Mountains pluton	TM	Mo	~1400		Unpublished	JLW
		BSPZ-1	Barrel Springs pluton, Piute Mountains	BS	Mo	1427	27	[60]	
		EPZ-1	Barrel Springs pluton, Piute Mountains	BS	Mo	1421	14	[60]	
		EPZ-2	Barrel Springs pluton, Piute Mountains	BS	Mo	1416	17	[60]	
		SGZ-1	Piute Mountains pluton	PM	Mo	~1420		Unpublished	
		JW-100	dike in Piute Mountains	PM	Mo	1418	44	Unpublished	

[a] Crustal provinces that host granites: GR, Granite–Rhyolite; Ma, Mazatzal; Mo, Mojave; P, Penokean; Y, Yavapai.
[b] U–Pb zircon age references.
[c] WRVS, W R Van Schmus (Univ. Kansas); MEB, M E Bickford (Syracuse Univ.); KRC, K R Chamberlain (Univ. Wyoming); JLW, J L Wooden (U.S. Geological Survey).

Table 2
Hf-isotope data from zircons in 1.3–1.4 Ga Laurentian granitoids

Sample	Map reference	Age (Ma)	$^{176}Hf/^{177}Hf$[a]	± (10^{-6})	$^{176}Lu/^{177}Hf$[b]	ε_{Hf} (present)[c]	±	ε_{Hf} (initial)[c]	T_{DM}–Hf model age (Ma)[d]
1. Southern Granite–Rhyolite province (1.5–1.3 Ga)									
TISH (A)	TI	1374	0.282169	10		−21.32	0.35		
TISH (A rr)	TI	1374	0.282164	6		−21.50	0.21		
TISH (B)	TI	1374	0.282152	4	0.00101	−21.93	0.14	7.68	1598
MOMC2	MO	1367	0.282125	6	0.00126	−22.88	0.21	6.34	1678
2. Central Yavapai province (1.8–1.65 Ga)									
KSMS-044	KS	1428	0.282035	9	0.00083	−26.06	0.32	4.88	1818
NBFN-001	NB	1436	0.282041	5	0.00093	−25.85	0.18	5.17	1806
RV-1C light (A)	OC	1442	0.282011	7	0.00059	−26.91	0.25	4.57	1849
RV-1C light (B)	OC	1442	0.282005	4	0.00035	−27.12	0.14	4.59	1847
SC-2	SI	1362	0.282069	7	0.00087	−24.86	0.25	4.60	1785
SD-2 (B)	SI	1377	0.282083	4	0.00089	−24.37	0.14	5.41	1745
CO-7	MG	1474	0.282065	4	0.00146	−25.00	0.14	6.34	1761
CO-9	MG	1460	0.282062	8	0.00112	−25.11	0.28	6.26	1755
NOB-1	HC	1441	0.282078	6	0.00070	−24.54	0.21	6.82	1704
3. Western Yavapai province (1.8–1.65 Ga)									
A-151a (A)	JP	1414	0.282012	16		−26.88	0.57		
A-151a (A rr)	JP	1414	0.282001	7		−27.27	0.25		
A-151a (B)	JP	1414	0.281999	5	0.00067	−27.34	0.18	3.45	1899
A-153 (A)	GM	1414	0.282019	13		−26.63	0.46		
A-153 (B)	GM	1414	0.282008	5	0.00115	−27.02	0.18	3.31	1907
JW-122	YA	1421	0.282023	5	0.00109	−26.49	0.18	4.05	1865
JW-13	OR	1418	0.282011	5	0.00211	−26.91	0.18	2.59	1956
JW-15	OR	1418	0.281953	4	0.00106	−28.96	0.14	1.53	2023
B565	BM	1400	0.282055	4	0.00120	−25.36	0.14	4.63	1813
4. Granite–Rhyolite province (1.5–1.3 Ga)									
ILST-003	IL	1465	0.281931	5	0.00089	−29.74	0.18	1.95	2033
KSMI-4 (A)	KM	1361	0.282012	30		−26.88	1.06		
KSMI-4 (A rr)	KM	1361	0.282001	6		−27.27	0.21		
KSMI-4 (B)	KM	1361	0.282007	5	0.00128	−27.05	0.18	2.00	1950
KSDG-3	KD	1339	0.281977	5	0.00090	−28.11	0.18	0.80	2009
IACK-001 (A)	KC	1433	0.281937	10		−29.53	0.35		
IACK-001 (B)	KC	1433	0.281920	5	0.00078	−30.13	0.18	0.96	2071
5. Mojave province (1.8–1.65 Ga)									
BW-1 (A)	BC	1404	0.282031	7		−26.20	0.25		
BW-1 (B)	BC	1404	0.281903	5	0.00078	−30.73	0.18	−0.28	2128
KCAZ98-10	LM	1390	0.281931	7	0.00054	−29.74	0.25	0.63	2059
JW-10	AD	1410	0.281874	4	0.00096	−31.76	0.14	−1.35	2200
JW-1164	SG	1410	0.281935	4	0.00090	−29.60	0.14	0.87	2059
JW-1168	SG	1410	0.281909	6	0.00077	−30.52	0.21	0.07	2110
JW-4	TM	1400	0.281922	5	0.00071	−30.06	0.18	0.37	2083
BSPZ-1	BS	1427	0.281890	8	0.00041	−31.19	0.28	0.12	2120
EPZ-1	BS	1421	0.281891	8	0.00030	−31.16	0.28	0.12	2115
EPZ-2	BS	1416	0.281881	5	0.00027	−31.51	0.18	−0.31	2139
SGZ-1	PM	1420	0.281944	4	0.00058	−29.28	0.14	1.72	2013
JW-100	PM	1418	0.281893	6	0.00029	−31.09	0.21	0.14	2112
6. Penokean province (1.9–1.8 Ga)									
VS70-91a	WR	1475	0.281875	45		−31.72	1.60		
MI 81-12	MI	1472	0.281867	5	0.00078	−32.00	0.18	−0.06	2166

consanguineous ACMG igneous suite. Taken together, these features appear to require melting of a fertile lower-crustal or upper-mantle source over large lateral distances following a major phase of crustal and supercontinent assembly.

3. Samples and methods

3.1. Sample selection

We obtained zircon separates from 26 previously dated granitoid intrusions emplaced within the Mojave (1.8–1.7 Ga), Yavapai (1.8–1.7 Ga), Mazatzal (~1.6 Ga), Granite–Rhyolite (1.5–1.3 Ga), and Penokean (1.9–1.8 Ga) crustal provinces (Fig. 1 and Table 1). These provinces were all accreted to the southern Archean nucleus of Laurentia represented by the Superior and Wyoming provinces after about 1.9–1.8 Ga (see [6,16,20] for review of their major geological features).

The Mojave and Penokean provinces show isotopic evidence of older inheritance [13–15,38–40], but the other provinces have a more juvenile isotopic character. The granites examined in this study are broadly representative of the A-type magmatic belt in North America. Our sample suite is intended to maximize geographic coverage and sample a broad range of Paleoproterozoic and younger basement provinces. Most intrusions are presently exposed, but many of the granitoids in the central Great Plains are covered by Paleozoic sedimentary rocks and known only from drill-hole sampling [6]. Most of the granites are part of the high-$f(O_2)$ magnetite series [3], but some in Colorado belong to the peraluminous two-mica group. The ages of the zircon samples are well characterized by conventional isotope-dilution TIMS U–Pb methods (Table 1) and include both major age groups (~1370 and ~1450–1475 Ma). Nd-depleted mantle model ages have been determined for some of the granites, particularly in the southwestern and mid-continent regions [6,13,14,41]. For five of the intrusive units (map units SI, MG, OR, SG, and BS, intruding the Mojave, western Yavapai and central Yavapai provinces; Fig. 1), we analyzed zircon from more than one individual sample, providing a check on the internal isotopic variability within a single intrusion. Samples from the mid-continent area and Colorado Front Ranges include granites with both ~1370 and ~1450 Ma ages, allowing us to assess variability within a basement province relative to crystallization age.

3.2. Analytical methods

A full description of our analytical methods is presented in Appendix A and only a brief summary is given here. Approximately 10 μg of zircon (typically 1–12 grains; average of 6) were handpicked from the zircon separates under a binocular microscope on the basis of clarity and lack of inclusions or fractures and loaded into 0.5 ml Savillex PFA screw-top vials. Zircons were dissolved at 250 °C for approximately 48 h in HF/HNO_3 (~10 : 1) following the method of Parrish [42]. Following dissolution and conversion to chlorides, solutions were spiked with a zircon-specific mixed ^{176}Lu–^{180}Hf tracer [43]. Hafnium and HREEs were separated from the zircon solution using micro-columns with 0.18 of Dowex AG50W-X12 cation resin using established methods [43–45] and purified with a repeat of this procedure. Lu was separated using columns with 1.0 ml of LN Spec resin leaving a small amount of Yb in the sample in order to correct for Lu mass bias during isotopic analysis [43]. Hf and Lu isotopic compositions were measured on a ThermoFinnigan Neptune multi-collector ICP–MS at Washington State University. Analysis of the Hf standard JMC-475 during the course of this study yielded $^{176}Hf/^{177}Hf = 0.282145 \pm 15$ ($n = 10$). This variation is a reasonable estimate of the reproducibility of the samples (~±0.5 ε_{Hf} units), which is larger, in nearly all cases, than the reported analytical error in Table 2 based on in-run statistics (typically ±0.000004 to 0.000010). Following mass bias correction, measured Hf isotopic compositions of samples were

Notes to Table 2:
Lu and Hf concentrations were calculated but are not reported due to the large uncertainty in the grain weight estimates.

[a] All analyses measured in multi-grain (≤12, average 6) subsamples. Ratios normalized to $^{179}Hf/^{177}Hf = 0.7325$. JMC-475 Hf. Standard gave $^{176}Hf/^{177}Hf = 0.282145 \pm 15$, $n = 10$ over the course of this study. This compares to a long-term average for the WSU Neptune of 0.282147 ± 12, $n = 249$. Final ratios are normalized relative to $^{176}Hf/^{177}Hf = 0.282160$ for the JMC-475 Hf standard.

[b] Errors for $^{176}Lu/^{177}Hf$ are estimated to be approximately 0.2% [43].

[c] For calculation of ε_{Hf} values we used $^{176}Hf/^{177}Hf_{CHUR(0)} = 0.282772$ and $^{176}Lu/^{177}Hf_{CHUR(0)} = 0.0332$ [46].

[d] For Hf depleted mantle model ages we used $^{176}Hf/^{177}Hf$ and $^{176}Lu/^{177}Hf$ for the individual zircon samples to calculate their $^{176}Hf/^{177}Hf_{(i)}$ ratios at their crystallization ages. Projection back from zircon crystallization was calculated using $^{176}Lu/^{177}Hf = 0.0150$. The depleted mantle Hf evolution curve was calculated from present-day depleted mantle values of $^{176}Hf/^{177}Hf_{DM(0)} = 0.283225$ and $^{176}Lu/^{177}Hf_{DM(0)} = 0.038512$ [47]. See text for further details.

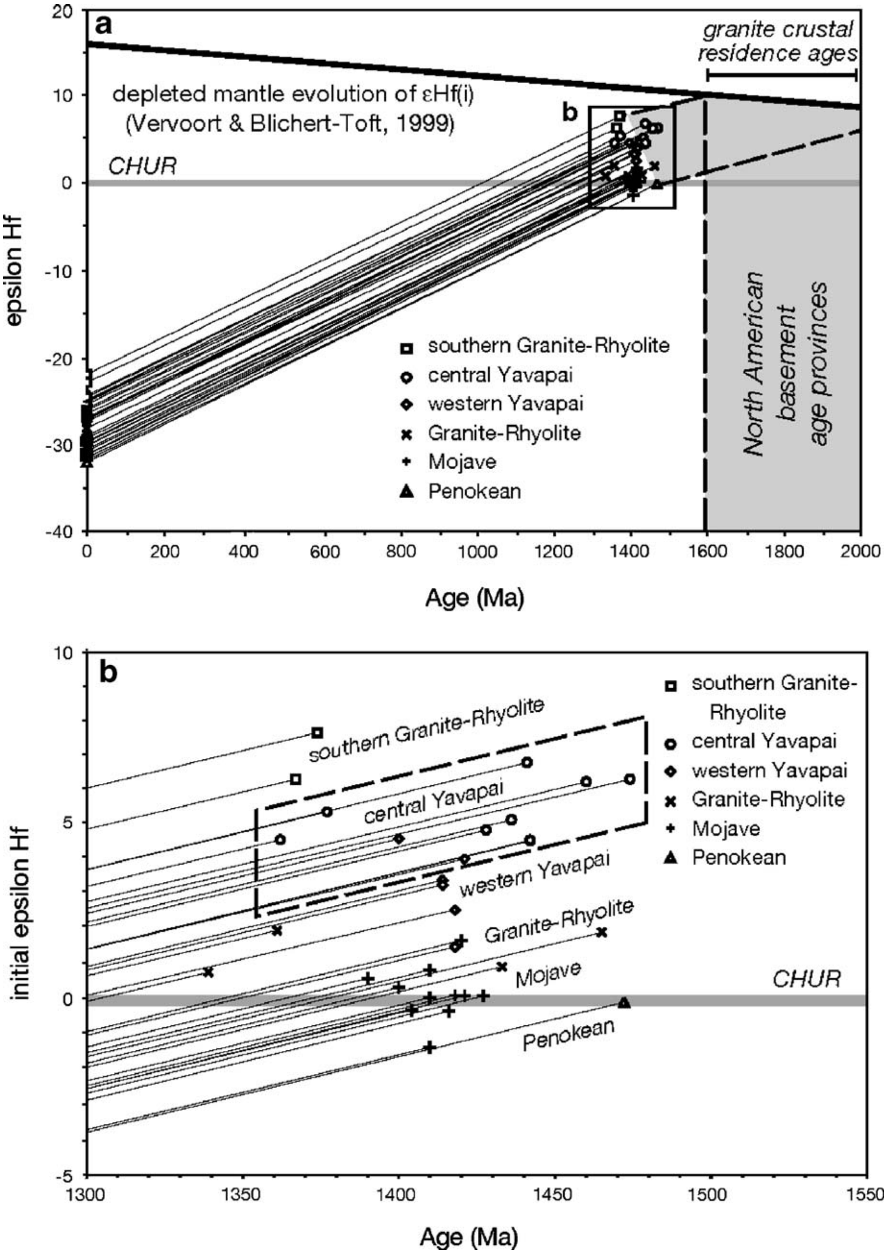

Fig. 3. (a) Age vs. ε_{Hf} values for Laurentian A-type granitoids, showing both measured and initial epsilon Hf values as function of crystallization age. Depleted-mantle Hf evolution curve from [47]. Projecting from the measured and initial ε_{Hf} values to the mantle-evolution curve yields crustal residence ages that correspond to the formation and Nd-model ages of 2.0–1.6 Ga crustal provinces that host the granitoids (shown by the shaded region). The shallower slope of the Hf isotope evolution prior to the formation of the zircons reflects the slightly higher $^{176}Lu/^{177}Hf$ of the presumed juvenile crust. See text for details. (b) Detail of the Hf evolution shown in (a), with enlarged scale to show initial ε_{Hf} values of all units.

adjusted relative to $^{176}Hf/^{177}Hf=0.282160$ for JMC-475. Lu isotopic measurements and $^{176}Lu/^{177}Hf$ isotopic determinations were made following the methods described elsewhere [43]. Epsilon Hf (ε_{Hf}) values were calculated using the present-day chondritic values of $^{176}Hf/^{177}Hf_{CHUR(0)}=0.282772$ and $^{176}Lu/^{177}Hf_{CHUR(0)}=0.0332$ [46].

4. Results

We determined Hf isotope compositions for 39 zircon separates from 31 different samples. The Lu–Hf isotope compositions of the Laurentian granitoid zircons are shown in Table 2 organized by their host province and ordered from most to least radiogenic. As a group, these zircons have present-day Hf isotopic compositions with a fairly narrow variation from 0.281867 to 0.282169. This corresponds to a range in present-day ε_{Hf} values from −32.0 to −21.3, a total range of just over 10 epsilon units (Fig. 3a). Zircons by nature have very low Lu/Hf ratios and the Laurentian zircons are no exception with an average $^{176}Lu/^{177}Hf$ value of 0.0009 and a range from 0.0003 to 0.0021. Because of these low Lu/Hf ratios, there is very limited radiogenic ingrowth of Hf over the ~1.4 Ga life of the zircons. Based on a $^{176}Lu/^{177}Hf$ ratio of 0.0009 and an age of 1.42 Ga, the total ingrowth of radiogenic Hf would result in an increase in the $^{176}Hf/^{177}Hf$ ratio of 0.000024, less than 1 ε_{Hf} unit. For the zircon with the highest $^{176}Lu/^{177}Hf$ ratio (0.0021 for JW-13), the total ingrowth over 1.42 Ga is about 2 ε_{Hf} units. In contrast, the $^{176}Hf/^{177}Hf$ ratio of the CHUR value, used to calculate epsilon Hf values at different ages, changes by 0.00916, or a little more than 32 ε_{Hf} units. These characteristics result in small changes in the $^{176}Hf/^{177}Hf$ ratios of the zircons over their history, but large, consistent changes in their ε_{Hf} values, as shown by parallel growth trajectories of these zircons in Fig. 3a. As a result, the initial ε_{Hf} values of these zircons, calculated at their crystallization ages (Table 2), have a narrow range of compositions from a low of ε_{Hf}(1.47 Ga)=−0.1 for MI-81-12 from a granite within the Penokean province, to a high of ε_{Hf}(1.37 Ga)= +7.7 for TISH from a granite within the southern Granite–Rhyolite province, a total variation of less than 8 ε_{Hf} units.

In spite of the fairly uniform nature of this zircon population as a whole, zircons from subgroups of the granitoids have different Hf isotopic compositions that correlate with the age and isotopic composition of their host provinces (Fig. 3b). For example, zircons from two granites intruding the Penokean province have an initial ε_{Hf} value of −0.1 (Tables 2 and 3). Similarly, 9 zircon samples from eight granites emplaced into the Mojave province have initial ε_{Hf} values of −1.4 to +1.7. The granites in these two crustal provinces have the least radiogenic isotopic compositions (lowest initial ε_{Hf} values) of all the Laurentian granites, averaging −0.1 and +0.2, respectively.

The granites inferred to intrude the mid-continent Granite–Rhyolite province have more radiogenic Hf isotopic values. Most of these have uniform compositions with initial ε_{Hf} values of +0.8 to +2.0, but two samples (TISH and MOMC2) have Hf isotopic compositions about 6 ε_{Hf} units higher. We divide these latter samples into a separate group that is geographically associated with the southern boundary of the province adjacent to the Grenville Orogen. These more positive ε_{Hf} values of the southern Granite–Rhyolite group are similar to the Nd isotopic signature of some granites from the southern mid-continent [13], in that they indicate derivation from young, mantle-derived crust, perhaps at the rifted edge of juvenile Mesoproterozoic terranes.

Samples from granites intruding the Yavapai province can be separated into central and western subgroups (Fig. 3b). Zircons from the central Yavapai group have uniformly radiogenic Hf (initial ε_{Hf}=+4.6 to +6.8), similar to granites from the southern Granite–Rhyolite province. The western Yavapai subgroup has somewhat less radiogenic Hf isotopic compositions (initial ε_{Hf}= +1.5 to +4.6).

Group averages of the data as listed in Tables 2 and 3 are compared in Fig. 4. An important feature of the Hf data is that within each province there is a striking uniformity of zircon Hf isotopic compositions. The initial Hf isotopic values of the granitoid zircons within each individual province have a total variation of 3 ε_{Hf} units or less. In addition, replicate analyses of seven zircon samples (KSMI-4, IACK-001, TISH, RV-1C, A-151a, A-153, and BW-1) show uniform compositions within a zircon population, even when distinguished by

Table 3
Mean Hf values of granites intruding Laurentian basement provinces

Province [a]	Granite age (Ma)	$^{176}Hf/^{177}Hf$ (initial)	± ($\times 10^{-6}$)	ε_{Hf} (present)	±	ε_{Hf} (initial) [b]	±	T_{DM}–Hf model age (Ga)	T_{DM}–Nd model age (Ga) [c]	Province age (Ga)
Southern Granite–Rhyolite (4)	1372	0.282153	20	−21.9	0.7	7.0	0.9	1.7–1.6	2.0–1.6	1.5–1.3
Central Yavapai (9)	1429	0.282050	28	−25.5	1.0	5.4	0.9	1.85–1.7	2.0–1.8	1.8–1.65
Western Yavapai (9)	1414	0.282009	27	−27.0	0.9	3.3	1.1	2.0–1.8	2.0–1.8	1.8–1.65
Granite–Rhyolite (7)	1393	0.281969	39	−28.4	1.4	1.4	0.6	2.1–1.95	2.0–1.6	1.5–1.3
Mojave (12)	1411	0.281917	42	−30.2	1.5	0.2	0.8	2.2–2.0	2.3–2.0	1.8–1.65
Penokean (2)	1474	0.281871	6	−31.9	0.2	−0.1	nd	2.2–2.1	2.6–1.9	1.9–1.8

[a] Number of zircon solutions analyzed in parentheses.
[b] Error for $\varepsilon_{Hf(i)}$ not determined because ^{176}Lu measured in only one Penokean sample (VS70-91a).
[c] Sources of Nd data: [6,13,14,38,40,41].

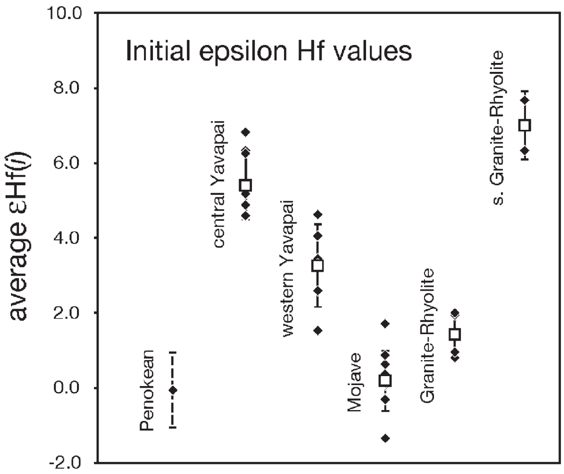

Fig. 4. Individual (black diamonds) and average (white squares) initial ε_{Hf} values of Mesoproterozoic granites grouped by the Laurentian provinces they intrude (data from Tables 2 and 3, with 2σ errors). Dashed-line uncertainties for Penokean granites assigned to be 1 epsilon unit; statistics could not be determined because initial ratio was calculated for only one sample of this group.

their color and magnetic properties (Table 2). These data indicate that individual intrusions are, to a first order, isotopically homogeneous. We interpret the average Hf isotope values as reflecting actual differences in the isotopic character of the granite magmas and, by inference, in their sources.

5. Discussion

5.1. Isotopic features of the A-type Laurentian granites

Hf isotope evolution trends for the A-type Laurentian granites are illustrated in Fig. 3. Growth lines connecting present-day with initial ε_{Hf} values are parallel and indicate closed-system isotopic evolution since crystallization. These growth trajectories project back through initial ε_{Hf} values to the depleted-mantle evolution curve [47], yielding crustal residence ages for the granites that correspond to the age of the crust they intrude. That is, the most radiogenic values (higher ε_{Hf}) are associated with the youngest host provinces, and the least radiogenic values (lower ε_{Hf}) are associated with the oldest crustal provinces.

One fundamental observation from the Hf isotope data is that the 1.48–1.36 Ga A-type granites cannot represent products of juvenile mantle melts; if they had been derived from melting of a mantle source, they would have ε_{Hf} values close to the depleted-mantle evolution curve (e.g., values of about +10 to +12 at ~1.4 Ga). To the contrary, the growth trajectories of the Hf isotopic composition of the zircons, and their likely parent material, intersects the depleted-mantle evolution curve at ages corresponding to the known ages of juvenile crust formation in the host basement provinces. The granites intruding younger crust (e.g., western Yavapai and southern Granite–Rhyolite provinces) have more mantle-like values simply because they have melted crust that has not had time to evolve from its juvenile (mantle) starting composition, whereas older crust (e.g., Penokean and Mojave provinces) has had more time to evolve away from the mantle evolution curve to lower ε_{Hf} values.

The initial ε_{Hf} isotopic values of the granites, on first inspection, appear to be a coherent group as plotted in Fig. 3a, but on the expanded scale of Fig. 3b samples from different basement provinces show distinct compositions. Also illustrated in Fig. 3b is the similarity of Hf isotope values for granitoids with different ages within a single basement province. In both the central Yavapai and Granite–Rhyolite provinces, for example, ~1360 and ~1450 Ma granites have Hf isotopic compositions that evolved from isotopically similar sources, as illustrated by the box around the central Yavapai samples in Fig. 3b. This pattern indicates that even though individual intrusions may have formed 100 Ma apart, these granites share a common crustal source.

Although the relative contributions of crust and mantle to the genesis of the Laurentian A-type granites is difficult to precisely quantify due to uncertainties in Hf isotopic compositions and concentrations within crust and mantle end-members, we can nevertheless make some general approximations. For these estimates, we assume that a mantle-derived source will have a Hf isotopic composition defined by the depleted-mantle curve [47] and a Hf concentration of 2.5 ppm (estimated from MORB data). We estimate the Hf composition of juvenile Proterozoic crust by letting it evolve from a depleted-mantle composition using a $^{176}Lu/^{177}Hf$ ratio of 0.015. This Proterozoic crust has an estimated Hf concentration of 5 ppm (both $^{176}Lu/^{177}Hf$ and Hf concentration are estimated from Vervoort and Blichert-Toft [47]). These parameters yield crustal contributions in excess of 90% for nearly all cases, assuming reasonable minimum values of crustal age. A large uncertainty in these calculations comes from the Hf isotopic composition of the crustal component, which is unknown and a function of age and petrogenetic history (i.e., whether it is entirely juvenile crust or not).

In contrast to our findings of significant crustal–melt fraction, some 1.4 Ga A-type granites are thought to have formed indirectly from a mantle source by partial melting of previously underplated tholeiitic lower crust [5,48], formed initially by decompression partial melting of upwelling mantle asthenosphere. Warming of the underplated lower crust layer in an extensional setting would result in formation of low-$f(O_2)$, high-T granite melts along with anorthositic and other melt compositions. As noted by its authors, this model has limited application to the broader association of Laurentian 1.4 Ga magmas because (a) partial melting of lower-crustal tholeiite cannot yield large volumes of granite melt, and (b) of all the Laurentian examples, only the Wolf River and Sherman batholiths show reduced compositions; the remainder are characterized as either metaluminous or peraluminous types that require significant melting of magnetite-bearing and/or metasedimentary crust. The extreme A-type geochemical and isotopic characteristics of the Sherman batholith [27,28,49], therefore, reflect atypical fractionation trends explained by magmatic differentiation of a tholeiitic source derived initially from a mantle reservoir.

The Hf-isotope depleted-mantle model ages for our samples are also consistent with the derivation of these granites predominantly from pre-existing crust. The depleted-mantle model ages are determined for each sample (Table 2) by calculating the intersection of the zircon/parent-rock growth trajectory with the depleted-mantle evolution curve [47], as shown in Fig. 3. The depleted-mantle curve was calculated from present-day values of $^{176}Hf/^{177}Hf=0.283225$ and $^{176}Lu/^{177}Hf=0.038512$. The zircon/parent-rock trajectory was calculated by taking the present-day $^{176}Hf/^{177}Hf$ value of the zircon and calculating its initial Hf isotopic value from its corresponding crystallization age and zircon $^{176}Lu/^{177}Hf$ ratio. In order to calculate the prior evolution of the crustal parent rock we assumed a $^{176}Lu/^{177}Hf$ value of 0.0150, which is the average value for juvenile Proterozoic crust mentioned above. Using this approach we determined depleted-mantle model ages that range from 1598 Ma for a sample from the southern Granite–Rhyolite province to 2166 Ma for the Penokean sample. Average Hf-isotope model ages for granites in each crustal province are listed in Table 3. Model ages from all the provinces are somewhat older than their formation ages, as expected. However, granites from three of the provinces (Penokean, Mojave and Granite–Rhyolite) show model ages that are significantly older, reflecting a crustal source with an average isotopic composition that is more evolved. The Yavapai and southern Granite–Rhyolite provinces yield model ages close to their formation ages, likewise suggesting more juvenile crustal sources. Nd-isotope model ages for igneous rocks in these provinces are consistent with the Hf-isotope results (Table 3).

5.2. Petrogenetic implications

Our data show that the Hf isotope compositions of individual Mesoproterozoic A-type granites in Laurentia vary by crustal residence age of the basement provinces they intrude (Fig. 5 and Table 3). Initial ε_{Hf} values show systematic differences with respect to the known crustal provinces of southern Laurentia, as well as when compared to major isotopic boundaries inferred from previous Nd- and Pb-isotope studies [6,13–15,38,40,41]. One fundamental observation is that the Laurentian A-type granites intrude only Proterozoic crust. With one known exception, none intrude the adjacent Wyoming and Superior Archean provinces. The lone exception to this pattern is part of the Sherman batholith in Wyoming. Most Sherman granite intrudes Paleoproterozoic rocks south of the Cheyenne belt suture, although one lobe also cross-cuts Archean gneisses that structurally underlie the adjacent Paleoproterozoic terrane [27,48]. This association of the Laurentian A-type granites with Proterozoic crust suggests that granite petrogenesis was controlled at least in part by processes dependent on the age and/or composition of the Proterozoic crust that they intrude.

The petrogenetic model that best accounts for the origin of the Laurentian A-type granites must explain the following isotopic and geologic relationships:

1. The principal composition of the intrusions is granite, and its Hf isotope composition indicates that fractionation from mafic parent magmas (e.g., primary mantle melts) is unlikely. The Hf isotope compositions, as do Nd, Sr and O isotopic data, indicate the granites were derived largely from melting of pre-existing crust rather than mantle. Even the anomalous Sherman batholith yields Nd-isotope values suggesting derivation from a ferrodiorite–anorthosite source mixed with up to 40% Archean crust [49].
2. There are no definitive calc–alkaline magmatic-arc signatures related to subduction-zone magmatic processes, as would be expected in an active continental-margin setting.
3. The granitoids were emplaced into only Paleoproterozoic and early Mesoproterozoic basement and are absent in Archean provinces. The resulting granitoids have crustal residence ages that match the age of the host terranes and, therefore, are consistent with derivation from 2.0 to 1.6 Ga crust.
4. There is a consistent time lag of 200–300 Ma between the last events affecting the Proterozoic host terranes and formation of the granite magmas,

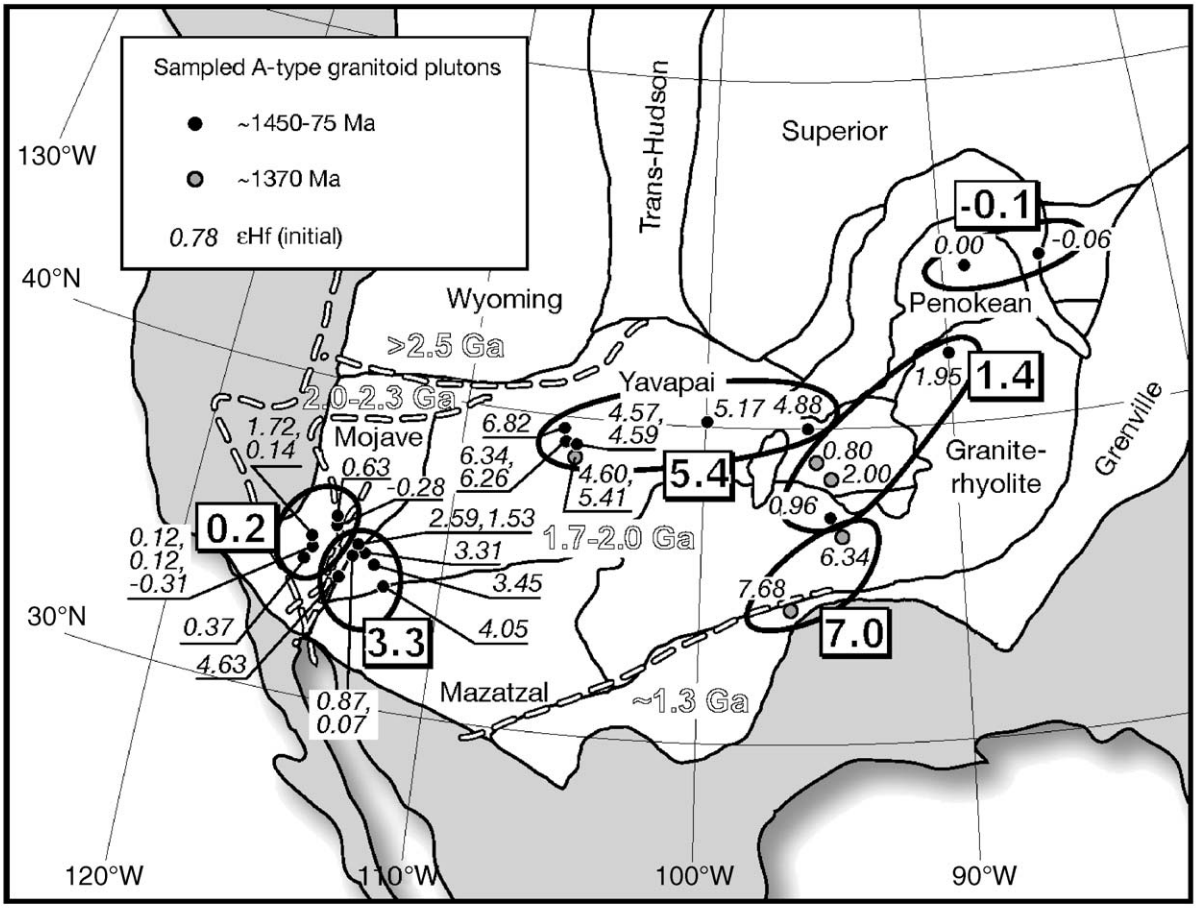

Fig. 5. Basement province map of southern North America (as in Fig. 1, here with crustal provinces unpatterned), showing $\varepsilon_{Hf(i)}$ values of individual Mesoproterozoic granite plutons. Circled groups (listed in Table 3) yield average $\varepsilon_{Hf(i)}$ values given in bold type. Major crustal province boundaries (long white dashed lines) taken from Nd- and Pb-isotope studies [13–15].

suggesting that the granite magmas were not directly related to earlier orogenic events.

5. The magma-forming process was a continental-scale event following major crustal growth.

The general similarity of our Hf isotope data suggest a high degree of uniformity in the Laurentian A-type magmas, yet resolvable differences reflect distinctive crustal signatures that indicate formation of the granites by crustal melting. Previous petrologic [1,3,26] and isotopic studies [1,3,13,14,41] arrived at the same fundamental conclusion that these magmas were generated by melting of pre-existing (mostly Paleoproterozoic) lower continental crust. Our Hf isotope data support and strengthen these conclusions by showing that the crustal residence time of the granites matches the formation age of the basement provinces that they intrude. The Hf data therefore offer strong support for regionally widespread partial melting of lower crustal sources of subtly varying composition and age.

A fundamental unresolved question is: What process(es) triggered melting? From the point of view of the whole magmatic province, two important clues stand out. First is the observation that the ~1.4 Ga granites occur exclusively within Paleoproterozoic to early Mesoproterozoic crust (Fig. 1), and they are absent in Archean provinces, with a single exception noted earlier [5,27]. Second, there is a time lag of some 200 Ma between the last major orogenic phase (Mazatzal contraction at ~1.65 Ga) and initial generation of the A-type granites [1,8]. Together, these relationships are most easily explained by melting of newly consolidated and thermally mature Proterozoic lower crust formed during continental margin development and its subsequent collapse along the southern margin of Laurentia [16,17,50], as suggested previously in post-orogenic melting models [4,8].

Numerical models of lithospheric plate movement, interaction, and thermal evolution [51] predict that continental lithosphere achieves mechanical stability over the short term following plate amalgamation or collision, yet as the welded plates age they build up heat by conductive heat flow from the mantle and intracrustal radiogenic heat production. Eventually, thermal expansion of underlying mantle and dynamic support of the overlying plate causes mechanical instability in the now warm continental lithosphere, leading to spontaneous supercontinent breakup. Crustal extension is an expected thermo-mechanical manifestation of post-orogenic relaxation or collapse [52]. The numerical models suggest that the time period between initial amalgamation and eventual breakup may be several hundred million years. By analogy, the Proterozoic crustal provinces of southern Laurentia represent a significant addition of juvenile arc-like lithosphere between about 2.0 and 1.6 Ga [16]. Although not strictly similar to the process of supercontinent amalgamation, this period of prolific crustal growth assembled a large volume of new lithosphere in a geologically brief period of time. The thermal evolution of this newly-formed lithosphere may have triggered lower crustal melting simply as a result of post-orogenic conductive heating, also causing widespread regional heating, metamorphism and resetting of low-temperature thermochronometers at higher crustal levels where the granite bodies were emplaced [37]. Such a non-orogenic, non-rift origin for the magmas is consistent with the large volumes of Mesoproterozoic granite emplaced as epizonal magma bodies (up to 35% of exposed area in some regions) across a significant part of Laurentia.

In contrast to the post-orogenic crustal melting hypothesis, other models for the origin of the Laurentian A-type granites fail to explain significant aspects of their occurrence and geochemistry. The Hf isotopic data reported here show that these granites are not dominated by mantle sources, which make plume and rift origins less tenable. A mantle plume origin is also inconsistent with the distribution of penecontemporaneous granite intrusions across a significant part of southern Laurentia. A rift origin is unlikely because of a lack of mantle isotopic signatures and associated widespread rift-related sedimentary and volcanic deposits. Generation of granite melts by fractional melting of previously underplated mafic lower crust, perhaps produced by decompression melting or advective heating during plume rise or crustal rifting, is also unlikely because of the significant proportion of melting required and the close relationship of the Hf isotopic composition of the granites to their host crustal provinces.

Emplacement of a widespread mafic underplate at the base of previously accreted Paleoproterozoic crust is, however, a compelling source of advective heat to cause crustal melting. Xenoliths of mafic granulite and other lithologies yielding ages of 1.75–1.40 Ga provide evidence of Proterozoic mafic lower crust in the Four Corners area [53–55]. Likewise, some seismic data indicate the presence of a laterally widespread mafic lower crustal layer [56], although the age and continuity of such a layer is disputed [57]. In order to explain crustal melting by heating from a mafic crustal underplate, such models also need to account for a lack of mantle-derived mafic melt in the granite province and, more importantly, generation of crustal melt on the vast scale observed.

Recent debate in the literature has focused on orogenic versus anorogenic origins for the Laurentian A-type granites, in which authors have addressed earlier suggestions for intrusion associated with “orogenic” or “tectonic” events [9–12]. Detailed discussion of this topic [4,26] is beyond the scope of this paper, but we concur with others [4] that widespread low-grade heating in older country rocks and localized development of foliations do not constitute evidence for a widely distributed orogeny. From a geochemical perspective, the lack of an arc-like geochemical and isotopic signature in these rocks is inconsistent with an active-margin origin, although melting of thickened continental crust such as in the Andean or Tibetan plateaus cannot be ruled out. In collisional regimes characterized by crustal thickening, high heat production and low conductive heat loss can trigger lower crustal melting [58]. A-type granites could be generated over a wide region that has crustal isotopic signatures such as we have measured. However, in such a setting, the generation of crustal melt is a consequence of thickening, rather than subduction of oceanic lithosphere directly. Thus, among the most commonly cited models of A-type granite petrogenesis – crustal melting by underplated mantle-derived mafic magmas, craton–margin orogenic magmatism, and melting within thickened orogenic crust – the latter best explains the regional characteristics and isotopic patterns observed within the Laurentian province.

5.3. Isotopic structure of southwestern Laurentia

Comparison of our Hf-isotope data with Nd and Pb signatures from the 1.4 Ga granites helps to refine the isotopic structure of Laurentia. Broadly, there is good correlation of the isotopic provinces defined by each system (Fig. 5), and the isotopic compositions of Proterozoic to Cenozoic granites have long been used to map crustal provinces in Laurentia [13,14]. Some disparities exist, however, about the location and nature of province boundaries, such as between the Mojave and younger provinces to the east. Granites from western Arizona, for example, with the exception of those near Olea Ranch (sample JW-15; see Bryant et al. [59]), show consistent initial ε_{Hf} values of +2.1 to +3.4 (Table 2 and Fig. 5). Bryant et al. [59] interpreted Pb-isotope data from these and other igneous bodies to indicate that rocks in western Arizona should be included in the Mojave crustal province, and that the Mojave–Yavapai boundary passes through west-central Arizona rather than along the general trend of the Colorado River. In contrast, the Hf isotope values for the western Yavapai province as defined here support the interpretation of others [14,15] that crust underlying this area is distinct from older, more evolved crust of the Mojave province in eastern California (average $\varepsilon_{Hf(i)}$ = +0.2). The combined Nd, Pb and Hf data therefore support the idea of a major Yavapai–Mojave crustal boundary generally near the Colorado River. Our Hf data are consistent, however, with the suggestion that granites in western Arizona have a relatively uniform crustal source [59]. It is likely that the largely covered Yavapai–Mojave crustal boundary is structurally complicated and not a simple, steep geological boundary. Therefore, without detailed sampling it will be difficult to resolve its position with much certainty using the regional isotopic approaches of this and previous studies.

Even in cases considered to be far-removed from older province boundaries, different isotopic data lead to apparently contrary results. In eastern California, for example, Gleason et al. [60] interpreted Nd- and Pb-isotopic data from the 1.42 Ga Barrel Spring pluton (corresponding to three zircon samples presented here, BSPZ-1, EPZ-1 and EPZ-2) to indicate a magmatic source in either enriched lithospheric mantle or metamorphosed mafic lower crust. Although the Barrel Spring pluton intrudes crust thought to represent the Mojave province, its Nd-isotope depleted-mantle model ages (1.9–1.7 Ga) and initial ε_{Nd} values (−2.6 to −0.3) are interpreted to be incompatible with a source like that of typical Mojave province crust [60]. Similarly, Pb-isotope results suggest an affinity with somewhat younger central Arizona (Mazatzal type) crust rather than that of the Mojave province. In contrast, our Hf isotope data (initial ε_{Hf} values of −0.3 to +0.1 and model ages > 2100 Ma for the Barrel Spring pluton; Table 2) are consistent with derivation of these granitoids largely from pre-existing Mojave crust. Variations in the Nd-, Pb-, and Hf-isotope compositions between the Barrel Spring pluton and the broader Mojave province illustrate that there may be minor isotopic decoupling in some magmatic systems, perhaps due to mixing of crustal and mantle sources along a conjectured lithospheric boundary straddling the California–Arizona border [60].

Granites in the central Yavapai province (sample locations from the central Colorado Rockies eastward to Kansas and Nebraska; Fig. 5) show distinctly more positive initial ε_{Hf} than in most other areas (average $\varepsilon_{Hf(i)}$ = +5.4), indicating more juvenile sources as compared to granites in all other provinces except the southernmost Granite–Rhyolite province. Zircon U–Pb data for Paleoproterozoic bimodal igneous rocks in this part of the Yavapai province in Colorado show Archean and early Paleoproterozoic inheritance [61]. The older zircon ages, including some in the range of 1878–1814 Ma, were interpreted as xenocrystic cores that were preserved during formation of the Paleoproterozoic magmas. From this U–Pb evidence, Hill and Bickford [61] suggested that Wyoming-type and Trans-Hudson/Penokean (pre-Yavapai) crust extends southward across what is commonly interpreted as a juvenile continental-margin accretionary belt [6]. Some Nd-isotope data [62], on the contrary, show both juvenile and evolved sources for these igneous rocks, suggesting that the Paleoproterozoic magmas either incorporated some sediments containing older detrital zircons or originated in a section of heterogeneous crust. We find no indication from the Hf-isotope data for the presence of major Archean and early Paleoproterozoic lower crust in this region; the relatively positive Hf values, among the highest in our sample suite, rather indicate more juvenile compositions for sources of the Mesoproterozoic granites. Furthermore, they are unlike compositions of granites known to intrude the Penokean belt itself (Table 3). We concur with others that Proterozoic igneous rocks intruding the Yavapai province (including 1.7, 1.4, and 1.3 Ga ages) are the product of crustal melting [62], but the Hf isotope data indicate a younger, less evolved basement source. The central Yavapai belt and its boundary with the Archean Wyoming province clearly merit more detailed study.

We emphasize that the broad geographic distribution of the samples included in this study, cutting through a variety of crustal provinces, was chosen to address first-order questions of sources during magmagenesis. Our data are best explained in terms of lower crustal melting over a broad region, and they are generally compatible with the results from more detailed studies [13,14,59,60] that help to define the position and significance of regional isotopic boundaries. Our study does not have sufficient sample density to alter or refine these province boundaries in any significant way; rather, it shows the utility of using the Hf isotopic compositions of zircons to gain additional insight into crustal evolution. More detailed sampling would be required in certain province boundary areas to help resolve some of the remaining problems of crustal architecture.

5.4. Comparison with other Mesoproterozoic A-type granites

Some notable similarities exist between the Laurentian A-type granites and similar Mesoproterozoic rapakivi occurrences worldwide, notably in the Brazilian and Fennoscandian shields. For example, in the southwestern Amazonian craton of Brazil, a series of granites were emplaced in Paleoproterozoic to Mesoproterozoic crust between about 1600 and 970 Ma [63,64]. The ~1400–1300 Ma Santo Antônio–Teotônio intrusive suites were emplaced following the Rondônian–San Ignacio orogeny, considered to be of transpressional or oblique collisional type [63]. An association with coeval mafic and ultramafic magmas and intracontinental rift sedimentary rocks suggests that the rapakivi granites were genetically tied to continental breakup. Likewise, some slightly older Mesoproterozoic rapakivi granites from the Goiás province in the central Brazilian shield [64] are interpreted as the result of lower-crustal anatexis caused by earlier crustal thickening. Older A-type granites are also known (e.g., ~1.9 Ga granites in the Rio Maria region of the eastern Amazonian craton [65]), which show bimodal compositions, association with extensional deformation, dike swarms and thinned crust, and Nd-isotope signatures suggesting melting of previously stabilized lower crust caused by mafic magma underplating. A mechanism for generating a mafic crustal underplate is uncertain but in general is thought to be related to continental rifting. In all cases, the A-type rapakivi granites of the Brazilian shield show geochemical and isotopic characteristics indicative of post-orogenic crustal melting, either by crustal thickening or by mafic underplating.

In Finland, 1.65–1.54 Ga A-type granites emplaced within the 1.89–1.88 Ga Svecofennian Orogen represent the classic rapakivi suite (summarized by Haapala et al. [66] and Elliott et al. [67]). These rocks have within-plate mineralogical and geochemical characteristics suggesting dehydration melting of intermediate to felsic lower crust during incipient or aborted rifting of previously "cratonized" Paleoproterozoic and Archean continental crust. The cause of melting is uncertain but is commonly attributed to magmatic underplating associated with upwelling of subcontinental mantle. Isotopic trends across the Mesoproterozoic suite offer important constraints on magmagenesis. First, the O-isotope compositions of zircons in these rapakivi granites show decreasing values from north to south, independent of intrusion age, corresponding to lithologic and age discontinuities in the host basement terrains [67]. Second, whole-rock Nd-isotope compositions show the same systematic trends from western to southern Finland, with less juvenile ε_{Nd} values in the south indicating derivation from distinct Paleoproterozoic juvenile sources [21,67,68]. Thus, O and Nd isotopes both show systematic variations across older Paleoproterozoic terranes that reflect different compositions of lower crustal sources and, like their younger Laurentian counterparts, these variations occur independent of intrusion age (occurring in both 1.88–1.87 and 1.65–1.54 Ga post-orogenic granite suites). Although the magma sources are clearly crustal, it is uncertain if the cause of melting is active mantle heating or radiogenic warming of previously thickened continental crust.

5.5. Hf in zircon as a provenance tool

The Hf isotope compositions of the Laurentian granites, in addition to their age, may provide unique paleogeographic tracer information for testing proposed supercontinent reconstructions. Based on the distinct isotopic signatures of the 1.4 Ga Laurentian A-type granites, for example, it may be possible to use Hf isotopes to link detrital zircons from Neoproterozoic and younger sedimentary rocks with source terrains carrying Laurentian characteristics. Fig. 6 shows one of many proposed paleogeographic reconstructions of the Rodinia supercontinent in late Neoproterozoic time [69]. Most reconstructions for this time period agree that the extant Mesoproterozoic and older cratons of Australia and East Antarctica were adjacent, but the other intercratonic relationships are less certain and the subject of ongoing debate. Virtually all of the mutual cratonic boundaries shown here are controversial in some way. Of particular interest in the context of this study, however, is that in this reconstruction, as well as in many others, the ~1.4 A-type granitoid province in Laurentia lies centrally within Rodinia. Other occurrences of Mesoproterozoic granitoid intrusions are known in the southern African, Australian, Baltic, Brazilian, and Indian shields (Fig. 6), but most of

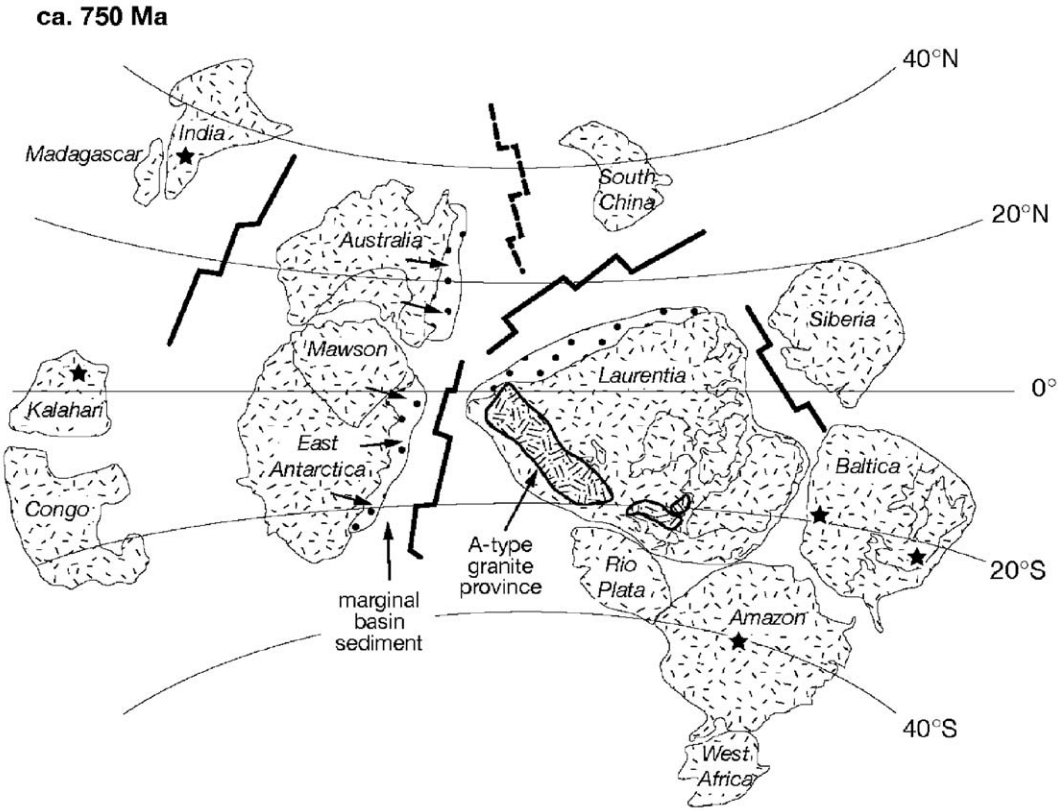

Fig. 6. Paleogeographic reconstruction of Rodinia showing one of many postulated late Proterozoic distributions of major cratons (after [69]). Inferred Neoproterozoic rifts and spreading ridges shown by heavy black lines. Extent of Mesoproterozoic A-type granite province in Laurentia shown by double hachure pattern; other Mesoproterozoic (1.40–1.55 Ga) intrusions of rapakivi granite, charnockite and anorthosite shown by stars. Neoproterozoic and lower Paleozoic passive margin siliciclastic deposits in Austral–Antarctic region (stippled) contain notable populations of ~1.4 Ga igneous zircon [70,73] that could have a source in the Laurentian A-type granite province, or within an extension of this igneous province into East Antarctica, where it is now ice-covered. With a central location in Rodinia, the distinctive age and Hf isotope compositions of the 1.4 Ga granites in Laurentia could provide a means to test various paleogeographic models.

these are volumetrically minor compared to those in Laurentia [7]. As such, the Laurentian magmatic province may arguably be an important source of continentally derived detritus received by marginal basins adjacent to a number of shield areas.

To address the ambiguity of simple age correlations, integration of both age and tracer information could provide a more precise discriminant for use in detrital zircon studies. For example, although the East Antarctic shield is largely ice-covered, isotopic and geochronological data provide permissive evidence for extension of the ~1.4 Ga Laurentian granitoid province into East Antarctica [70]. First, Nd-isotope data obtained from ~500 Ma granites in the Ross Orogen suggest that crust underlying parts of this Gondwana-margin orogen includes Paleo- and Mesoproterozoic igneous basement like that in western Laurentia [71,72]. Second, detrital zircons in upper Neoproterozoic and Lower Cambrian sandstones, deposited along the rift margin of East Antarctica and derived from the East Antarctic shield (Fig. 6), include significant proportions of 1.8–1.6 Ga and 1.5–1.3 Ga grains [70,73]. There are no known basement sources of these ages in present-day Antarctica and Australia, but if present their traces are expected in siliciclastic sedimentary basins distributed along the Austral–Antarctic margin. Both of these results suggest that a composite Paleo- and Mesoproterozoic igneous basement province may be present beneath the Antarctic ice cap, and that it has characteristics similar to the Paleoproterozoic Laurentian accretionary provinces punctuated by ~1.4 Ga A-type granitoids. To date, no plutons of this age have been reported from Antarctica, but comparing the Hf isotope compositions of the Antarctic detrital zircons with those from the Laurentian granitoid belt could provide a means of evaluating the Laurentian connection to Austral–Antarctica.

Despite uncertainties in geological, isotopic and paleomagnetic clues to paleogeography, applying different types of geological correlation tools may test existing models. In this case, it may be possible to uniquely correlate basin and source by tracing distinctive clastic isotopic signatures. If the Hf-isotope composition of the Laurentian ~1.4 A-type granites proves distinctive from other magmatic sources, then it might be used as an effective isotopic tracer. Successful application of Hf isotopic compositions as a provenance discriminator in detrital zircon will require a broader Hf isotope database from potential igneous source terranes with distinctive age and tectonic characteristics. The results from this study provide reference data for a large continental igneous province with a unique age signature to which detrital zircon compositions can be compared in the future.

6. Conclusions

1. Mesoproterozoic A-type granites emplaced within composite, heterogeneous Proterozoic crust of Laurentia yield a narrow range of Hf isotope values and Hf-isotope depleted-mantle model ages reflecting different 2.0–1.6 Ga crustal sources. Calculated initial ε_{Hf} values discriminate the granites by age of the crust that they intrude, but are independent of intrusion age over the period between about 1.45 and 1.35 Ga.
2. All Laurentian granites represent dominantly crustal melts; although a mantle geochemical contribution cannot be ruled out, if present it must be minor. The clear evidence for melting of lower crustal sources and minimal mantle contributions eliminates models that require formation of A-type granites primarily by fractionation from mantle-derived parental magmas.
3. The distinct age and Hf isotope signature of these Mesoproterozoic igneous zircons may prove useful as a provenance tracer in detrital zircon suites from Neoproterozoic and younger siliciclastic deposits worldwide. In addition to applicability for correlating igneous provinces themselves, for example, the Hf-isotope values of ~1.4 Ga detrital zircons may help to establish dispersal patterns from various igneous sources to sedimentary deposits flanking the Rodinia supercontinent.

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Appendix A. Detailed analytical methods

Approximately 10 μg of zircon (typically 1–12 grains; average, 6) were handpicked from the zircon separates under a binocular microscope. Zircons from individual sample populations were generally uniform in size, shape, color, and clarity. Grains were chosen for analysis based on clarity and lack of visible inclusions or fractures. Photomicrographs of the zircon grains were used to estimate grain dimensions in order to calculate the approximate sample weight for the purposes of spiking. These zircons were loaded into pre-cleaned 0.5 ml Savillex PFA screw-top vials along with 0.35 ml of a ~10:1 mixture of concentrated HF and HNO_3. Dissolution of the zircons followed the method of Parrish [42]. Sample beakers (16 total in a batch) were capped loosely and placed in two layers in a Teflon liner for the large-capacity Parr dissolution bomb (model 4748). Approximately 5 ml of concentrated HF was added to the Teflon liner to provide vapor pressure within the Parr bomb. The bomb was then sealed tightly and put in an oven at 250 °C for approximately 48 h.

Following cooling of the Parr bomb, the zircon capsules were removed and rinsed and the solutions were transferred to clean 7 ml Savillex beakers to which an appropriate amount of zircon-specific mixed ^{176}Lu–^{180}Hf spike had been added (for spike information, see Vervoort et al. [43]). These solutions were fluxed in the capped Savillex beakers overnight to facilitate sample-spike equilibration and subsequently dried down. A small amount (50 μl) of a H_3BO_4/HCl mixture (2 : 1 ratio of saturated H_3BO_4 to 2.5 M HCl) was added to each capsule, capped tightly, and allowed to heat at ~100 °C on a hot plate. Capsules were then uncapped, solutions were dried, and ~1 ml of 6 M HCl was added to each capsule and dried down. Finally, another 1 ml of 6 M HCl was added to the samples, the capsules were sealed and allowed to flux on a hot plate for 6+ h, and subsequently dried. This procedure allows for the conversion of fluorides to chlorides, which is important for facilitating clean separation of Hf from the REEs.

Hafnium was separated from the zircon solution using a miniaturized version (0.18 ml resin volume) of the first-stage Hf separation columns described by others [44,45] using Dowex AG50W-X12 cation resin. Since Hf in zircon is a major element (~1%), other elements that have been of concern in the past (e.g., Zr for TIMS analysis; Ti for MC–ICP–MS) are either not a problem for analysis with MC–ICP–MS (Zr) or are not very abundant relative to Hf (Ti) in zircon. Rare earth elements (REEs), however, must be separated to avoid isobaric interferences with the Hf masses. In particular, Lu and Yb need to be completely removed because of the isobaric interferences of ^{176}Lu (2.6% abundance) and ^{176}Yb (12.72% abundance) on the radiogenic Hf isotope of interest, ^{176}Hf (5.23% abundance).

Prior to loading the samples on the columns, the samples were re-dissolved in 25 μl of 2.5 M HCl, diluted with 25 μl of H_2O, and heated for several minutes in tightly sealed capsules. Just prior to loading, 20 μl of 0.3 M HF was added to each solution to complex the Hf in the sample. Solutions were then loaded on the columns, the columns were washed with 20 μl of a weak HCl–HF solution (1 M HCl–0.1 M HF) and Hf was eluted immediately with two 50 μl additions of 1 M HCl–0.1 M HF. The columns were then washed with 120 μl of 1 M HCl–0.1 M HF, 1.8 ml of 2.5 M HCl, and Lu–Yb was eluted with 1.4 ml of 2.5 M HCl. The total time for this separation was about 1–2 h. The procedure of initially dissolving the bulk of the sample in HCl and then complexing the Hf with HF prior to loading is important and avoids forming REE fluorides. If REE fluorides are present, they will be eluted with the Hf and result in vexing interferences with the Hf. These interferences, in our experience, are difficult to accurately correct for, especially in spiked samples due to the elevated ^{176}Lu. To avoid any potential interferences, our procedure was to perform a quick clean-up of the Hf by repeating the first stage separation through the Hf elution. This procedure routinely produces Hf samples that are free of REEs. The Lu–Yb cut from the first stage columns can be cleaned up using columns with LN Spec resin leaving a small amount of Yb in the sample in order to correct for Lu mass bias during isotopic analysis [43]. In the case of zircon, it is often sufficient to avoid this separation because of the very low Lu/Hf ratios in zircons and the small correction required for radiogenic ^{176}Hf production in calculating initial ^{176}Hf/^{177}Hf ratios. The full procedure for Lu separation is described in Vervoort et al. [43].

Hf and Lu isotopic compositions were measured on the ThermoFinnigan Neptune multi-collector ICP–MS at Washington State University. Analysis of the Hf standard JMC-475 during the course of this study was ^{176}Hf/^{177}Hf = 0.282145 ± 15 (n = 10). This variation is a reasonable estimate of the reproducibility of the samples (~±0.5 ε_{Hf} units), which is larger, in nearly all cases, than the reported analytical error in Table 2 based on the in-run statistics (typically ±0.000004 to 0.000010). Following mass bias correction, the Hf isotopic compositions of all samples were adjusted slightly based on ^{176}Hf/^{177}Hf = 0.282160 for the JMC-475 standard. Lu isotopic measurements and ^{176}Lu/^{177}Hf isotopic determinations were made following the methods described by [43]. Epsilon Hf (ε_{Hf}) values were calculated using the chondritic values of ^{176}Hf/^{177}Hf$_{CHUR(0)}$ = 0.282772 and ^{176}Lu/^{177}Hf$_{CHUR(0)}$ = 0.0332 [46]. Although CHUR parameters for the Lu–Hf system are still a matter of debate [77], until there is a more definitive determination we use the Blichert-Toft and Albarède [46] values.

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